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MULTI-EVENT, MULTI-STRUCTURE EXPERIMENTAL VALIDATION OF HYSTERESIS LOOP ANALYSIS SHM

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ABSTRACT

Reinforced concrete (RC) and steel moment resistance frame (SMRF) structures are common in seismic zones. However, damage assessment after earthquakes can be problematic and subjective. This research applies fully automated hysteresis loop analysis (HLA) structural health monitoring (SHM) to several experimental cases. It quantifies accuracy and robustness for realistic structures over multiple events to demonstrate the ability to accurately monitor structures long-term. Data is analysed from: (1) experimental, scaled 12-story RC structure subjected to 2 events; (2) 2x12-story scaled RC structures undergoing 4 events; and (3) a full-scale 3-story E-Defence test with 6 ground motions. Accelerations of each DOF are recorded with lower rate displacements. Nonlinear hysteresis loops are reconstructed for each DOF for analysis. Changes in identified elastic story stiffness in these loops are used identify damage location and severity, and tracked for multiple events. The error from final identified stiffness to initial identified stiffness in a subsequent event assesses the method's ability to accurately and continuously monitor a structure. Elastic stiffness drops of 24%, 23% and 21% were identified for 2-4th DOF of the 12-story structure for the small ground motion though no visible damage was recorded, with large drops over 50% from initial values after the strong ground motion. Similar results are obtained for the 2x12-story RC frame test case, and the E-Defence test. More importantly, final and subsequent initial stiffness values were within 10% for all cases, and all but 2 were within 5%, clearly showing the consistency and reliability of this method. Initial stiffness for the first event was within 6% of calculated values. Overall, results indicate the HLA method automatically, accurately, and robustly detects and assesses damage location and severity for realistic structures across multiple events without human input, which has not been previously demonstrated by other methods.

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Multi-Event, Multi-Structure Experimental Validation of Hysteresis Loop Analysis SHM

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ABSTRACT

Reinforced concrete (RC) and steel moment resistance frame (SMRF) structures are common in seismic zones. However, damage assessment after earthquakes can be problematic and subjective. This research applies a hysteresis loop analysis (HLA) structural health monitoring (SHM) method for civil structures using automated hysteresis loop analysis to several experimental structures. The goal is to demonstrate accuracy and robustness over realistic structures, as well as over multiple events to demonstrate its ability to accurately monitor structures long-term.

Data is analysed from: (1) experimental, scaled 12-story RC structure subjected to 2 ground motions; (2) 2x12-story scaled RC structures undergoing 4 events; and (3) a full-scale 3-story E-Defence test with 6 ground motions. Accelerations of each DOF are recorded with lower rate displacement measure to rectify/baseline correct integrated displacement measures. Nonlinear hysteresis loops are reconstructed for each DOF, and divided into half cycles of response. Changes in identified elastic story stiffness in these half cycles are used as an index for damage localization and severity, and tracked over time. The error from final identified stiffness to initial identified stiffness in a subsequent event assesses the method's ability to accurately and continuously monitor a structure.

Elastic stiffness drops of 24%, 23% and 21% were identified for the second, third and fourth DOF of the 12-story structure under small input ground motion although no visible cracking or damage was recorded. Significant stiffness degradation was identified for the second, third and fourth DOF with stiffness losses over 50% compared to the calculated initial stiffness for the strong input ground motion. Similar results are obtained for the 2x12-story RC frame test case, and the E-Defence test. More importantly, the final and subsequent initial stiffness values were within 10% for all cases, and all but 2 were within 5%, clearly showing the consistency and reliability of this method. Initial stiffness values for the first event were also within 6% of calculated values.

Overall, results indicate the HLA method automatically, accurately, and robustly detects and assesses damage location and severity for realistic structures without human input. It does so with very high accuracy in identified values across multiple events, which has not been previously demonstrated in realistic experiments or tests by other methods. The measurements required are common, low-cost and robust, so the method can be readily implemented to provide immediate post-event feedback on damage status and location, which will enable faster and better decision making both immediately and during longer term recovery.

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Introduction

The main goal of structural health monitoring (SHM) is to create practical, efficient identification methods to clearly quantify changes in physical or modal parameters for damage assessment and localization for immediate post-event monitoring and long term decision making. To date, there is a significant gap between theory and practice in achieving this outcome, despite small scale laboratory and complex real structure structures being test [1-6]. In particular, method complexity and robustness, and/or significant data requirements prevent achieving this goal in civil SHM.

Story stiffness is a good damage index in SHM, because stiffness in some floors will be reduced if damage occurs in those layers [7]. In addition, stiffness degradation can reflect the severity of damage caused by both cumulative plastic deformation and cracking of concrete for SMRF and RC structures that are common in seismic zones [4]. Further, no complex exponents or calculations are required to calculate the damage index of story stiffness. Therefore, many current SHM methods, such as adaptive least mean squares (LMS) method [8, 9], extended Kalman filters (EKF) [10] and unscented Kalman filters (UKF) [11], identify changes in structural stiffness of selected baseline model parameters to reflect the severity of seismic damage. These model-based methods can successfully detect and quantify damage severity when the chosen baseline model is accurate representation of response. However, there is a significant, but unknown, risk of a poor and otherwise undetectable identification result when the chosen model does not match the dynamics of the actual measured system response since the actual outcome is not fully known [12].

The hysteresis loop analysis (HLA) method offers some significant advantages compared to the traditional model-based and non-parametric SHM algorithms. In particular, no differential equations need to be solved to evaluate modelling errors or optimise parameters [13-15]. Hence, the HLA method is based on fundamental mechanics, but not necessarily limited to a model structure. This approach thus allows the HLA algorithm to adapt to changes in how structure transfer load or demand across or between structural elements[12].

A further significant practical problem is few, if any, published SHM methods show results across multiple events without human intervention. There is a real need for automated methods that provide accurate results without human input to the identification problem. More critically they should operate such that, ideally, the identified ending stiffness of one prior earthquake event should match the identified beginning stiffness of the following event, which can be used to validate the continuity and accuracy of the SHM approach across different earthquake events, further indicating its ability to be used in long term monitoring.

However, as noted, to date, no prior research on nonlinear SHM methods has delivered these capabilities on either real or experimental, scaled structures. In addition, none have also considered with both low and high level events to see if they can detect and localize damage that may not be visible or observable in overall structural response or modal properties, but have significant impact on later larger responses. This aspect is critical for cases where large events are preceded by small events, as occurred in Christchurch, New Zealand [16].

This work experimentally examines the capability of the HLA method to meet all these needs. In particular, shaking table test data from: Structure A: a 1/10 scaled single-bay 12-story RC frame structure subjected to 2 ground motions; Structure B: a 1/10 scaled double-bay 12-story RC frame structure with damage prior to 4 events; and Structure C: a full scale 3-story E-Defence test with 6 ground motions. Only readily obtained acceleration measurements are used as input information to identify changes in elastic story stiffness as an index for damage localization and severity.

Methods

HLA Algorithm

A structural force-displacement hysteresis loop captures the linear and nonlinear structural load-deformation relationship that varies with time due to structural degradation and/or damage during strong earthquakes. The HLA algorithm identifies the stiffness components of any reconstructed hysteresis loop for each measured DOF using statistical methods. Briefly, it divides reconstructed hysteresis loops into individual half cycles in chronological order using the turning points where deformation is a local maximum or minimum. Each half cycle is assumed as an r -segment ($r=1, 2, 3$ or 4) linear model with $r-1$ breakpoints where segment slope is subject to change over time by half cycle. The estimation of the optimal r value for the selected multiple linear regression model is based on an F -type statistical hypothesis test [6, 14].

In particular, a sup F -type hypothesis test between the null hypothesis of a linear half cycle (1-segment) and alternative hypothesis of a nonlinear half cycle (2, 3 or 4 segments) defined [17]:

$$F(r = 2,3,4 | 1) = \frac{1}{N} \left(\frac{N - 2r}{2(r - 1)} \right) \frac{\delta' S' (S(ZZ')^{-1} S')^{-1} S \delta}{R_r} \quad (1)$$

where N is the number of observation in the selected half cycle; R_r is the overall SSR under the alternative hypothesis; $Z = \text{diag}(Z_1, \dots, Z_r)$ with Z_i as a function of breakpoints and unit; $\delta = (\delta_1, \dots, \delta_r)'$ is the regression coefficient vector with $\delta_i = (k_i, f_{bi})$, and S is the conventional matrix so that $S\delta = (\delta_1 - \delta_2, \dots, \delta_{r-1} - \delta_r)$. If the maximum value of $F(r=2,3,4/1)$ is smaller than the predefined critical value of 16.79, the half cycle is optimized as a linear regression model (one-segment) without breakpoint. Otherwise, a further $F(r+1/r)$, where $r=2$ and 3 , test is conducted to determine the number of breakpoints in the nonlinear half cycle, defined:

$$F(r + 1 | r) = n \left(\sum_{j=1}^r R_1(T_j) - R'_{r+1} \right) / R_r \quad (2)$$

where R_r is the overall SSR under the null hypothesis, R'_{r+1} is the overall SSR under the alternative hypothesis and $R_1(T_j)$ is the SSR at the j^{th} segment.

Once the optimal regression model for the hysteresis loop is identified, the elastic stiffness between any two DOFs can be deduced from the elastic segment of each half cycle and tracked over time for damage detection. All nonlinear post-yielding or return stiffness can also be found. The full details of the HLA method is presented in Zhou et al.[6, 14]. The flowchart of the HLA identification procedure is shown in Fig. 1.

Test and Test Structure

Structure A: a 1/10 scaled 12-story single-bay RC structure

Structure A is a 1:10 scale structural model of a 12-storey single-bay RC frame building in Fig. 2. The plan dimension is 600×600mm. Each storey has a 12 mm thick floor slab and the storey height is 300mm. The total height of the structure is 3600mm excluding a 200mm high rigid base. All

columns have constant 50×60mm cross section, and the beams are 30×60mm. Fig. 2 also shows the elevation and main dimensions of the test structure.

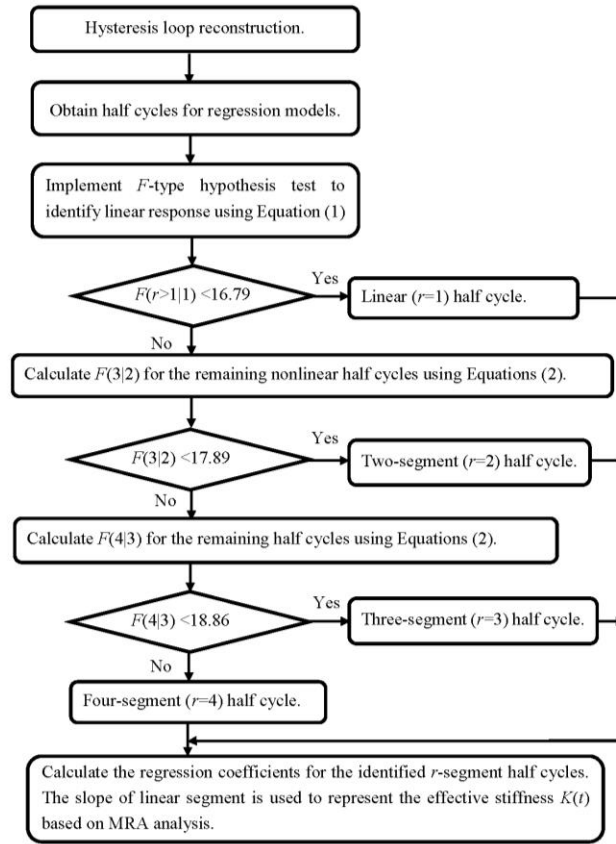


Figure 1. Flowchart of the HLA identification procedure.

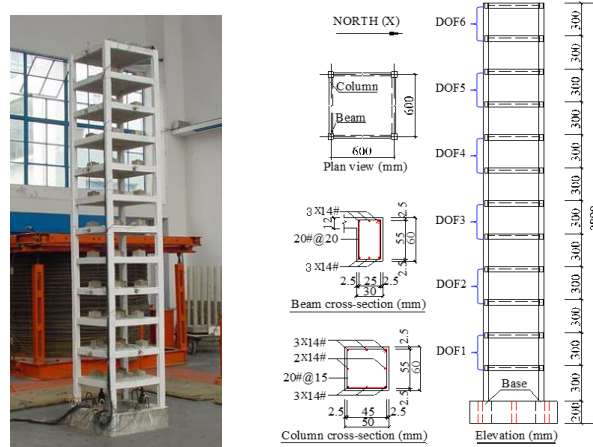


Figure 2. Photo and dimensions of Structure A.

Two stages of input ground motions based on the Shanghai artificial wave (SHW) were applied in the uniaxial direction (X direction), denoted as SHW1 and SHW2. The peak ground accelerations (PGA) are scaled to 0.09g for SHW1 and 0.258g for SHW2. The low and high intensity motions capture the possibility of unseen or unobserved, local damage becoming worse

in a subsequent large event. The accelerations of the test building were recorded in the shaking X direction at the base and every two levels, at a sampling rate of 250Hz. Measured accelerations thus include the 2nd, 4th, 6th, 8th, 10th and 12th (top) floor.

Structure B: a 1/10 scaled 12-story two-bay RC structure

Structure B is a 1:10 scaled structural model of a 12-storey two-bay RC frame building designed with two bays in the x-direction of shaking and one bay in the y-direction, as shown in Fig. 3. The dimensions in the two and one bay directions are 360mm \times 2 and 600mm, respectively. Each story consists of a 12mm thick floor slab and the story height is 300mm. Thus, the total height of RCF12 is 3600mm excluding a 110mm high rigid base. All columns have 50 \times 50 mm constant cross section, and beams are 30 \times 60 mm. considering the weight of non-structural elements and 50% live load, the artificial mass is 113.3kg for the top (12th) floor and 122.3kg for other floors.

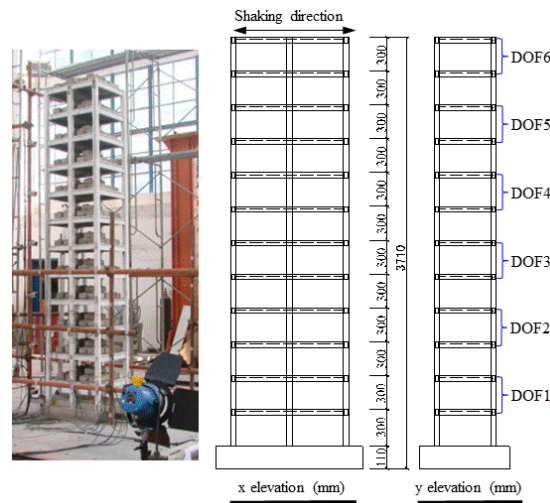


Figure 3. Photo and dimensions of Structure B.

Four ground motions were applied to Structure B in the uniaxial x-direction. The four input motions include the El Centro wave (El, PGA=0.15g) from the 1940 Imperial Valley earthquake in Southern California, Shanghai artificial wave (SHW, PGA=0.096g) based on the Shanghai Code for Seismic Design of Building, as well as the Wulong wave (WL, PGA=0.123g) and Shifang wave (SF, PGA=0.144g) from the 2008 Wenchuan earthquake. Accelerations and displacements were recorded at the base, 2nd, 4th, 6th, 8th, 10th, and 12th (top) floors, at a sampling rate of 62Hz.

It must be noted, Structure B was already damaged before these tests. Vertical cracks were visually observed in the beam-column joints in the lower floors before the initial El event. More vertical cracks were observed at these stories after the test. In addition, diagonal cracks were also observed in the third, fourth and fifth floors, which indicate plastic hinges had developed in these regions. Finally, vertical cracks were also found at the sixth and seventh stories after the test. However, this test represents many real situations, especially for severe aftershocks.

Structure C: a full scale 3-story E-Defense SMRF structure

Structure C is a full-scale Steel Moment Resisting Frame (SMRF) building, as shown in Fig 4. The building on the left hand is a normal building that is used in this work. The structure has three

stories and each story has a uniform height of 2870mm. The plan dimensions are 6405mm in the x-direction (NS) and 7320mm in the y-direction (EW). Rigid connections are designed between the H-shaped steel beams and cold-formed steel RHS columns. The seismic weights are 171.85kN, 171.85kN and 90kN for the first, second and third story, respectively. Input ground motions were applied in two horizontal (x , y) and vertical (z) directions. Three tri-axial accelerometers were installed on beams at each floor to record the structural response. Test events include six 3D earthquake excitations applied sequentially with different magnitudes, as listed in Table 1, with #01 referring to the first test event.

Table 1. Sequential shake table tests of Structure C in order given.

Test No.	Event	<i>PGA in y-direction</i>	<i>PGA in x-direction</i>	<i>PGA in z-direction</i>
#01	BSL2-18%	0.11 g	0.13g	0.01g
#02	Sannomal	0.22g	0.16g	0.01g
#03	Uemachi	0.30g	0.35g	0.01g
#04	Toshin-Seibu	0.62g	0.63g	0.06g
#05	Sannomal	0.21 g	0.15g	0.01g
#06	Nankai-Trough	0.87g	0.74g	0.03g



Figure 4. Photo of the 3-story E-Defence Structure C.

Results and Discussion

Hysteresis loops for the j^{th} DOF where accelerations are measured are reconstructed using the calculated restoring force f_j and the relative deformation $(x_j - x_{j-1})$ between DOFs. Over 95% half cycles are fitted with residual errors less than 5% for all the cases, indicating the identified piecewise regression models accurately capture the measured force-deformation relationship (hysteresis loop) of each story of the test structure under different earthquake excitations [6]. Therefore, the slope of the elastic segment of the selected half cycle can be used to accurately represent the effective story stiffness of the structure for damage assessment.

Structure A

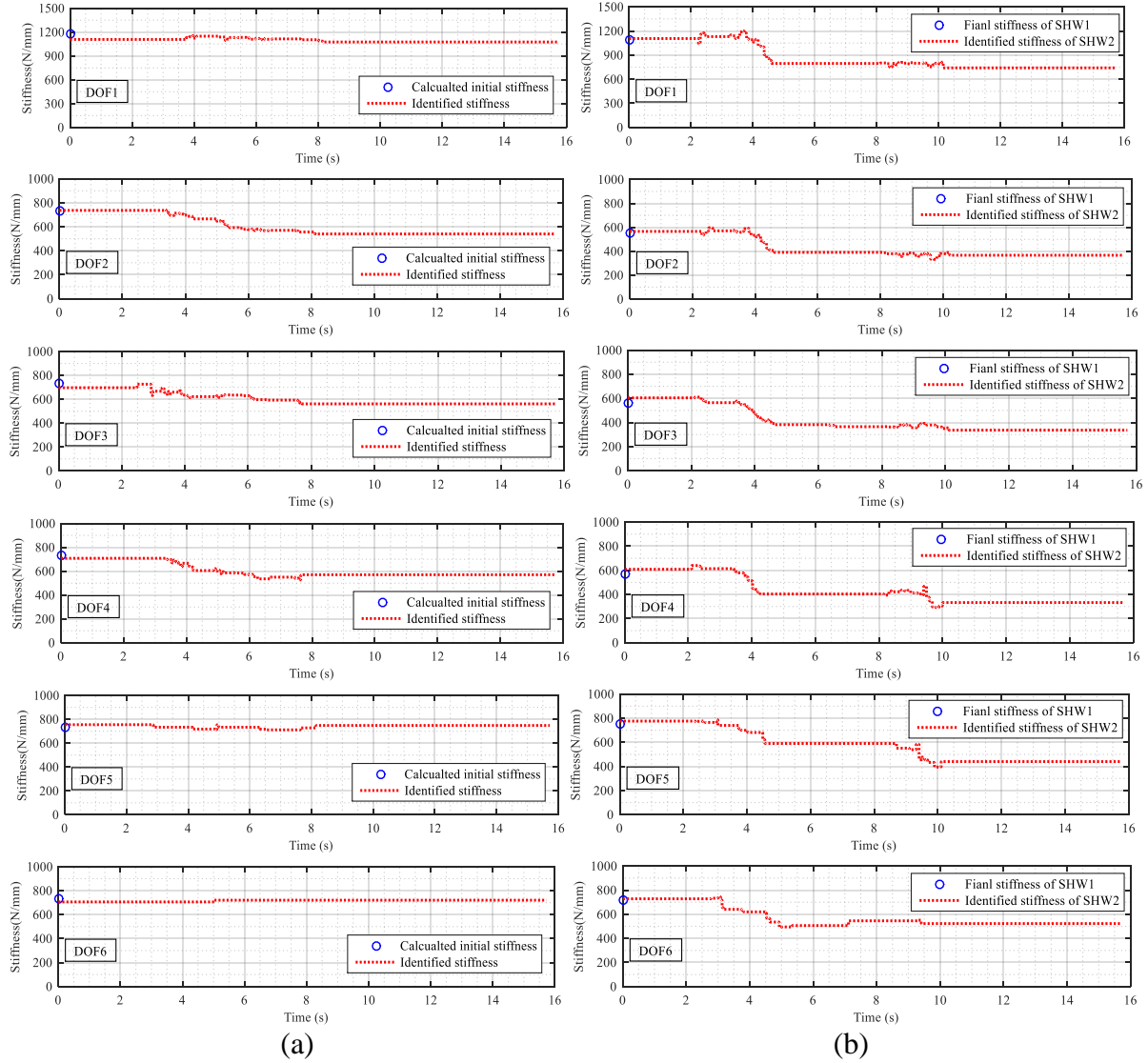


Figure 5. Identified evolution of the effective story stiffness of each DOF under (a) the small event SHW1 and (b) the larger event SHW2.

Fig. 5 shows the identified evolution of the effective stiffness of each DOF under the small event SHW1 and the large event SHW2, respectively. The calculated initial stiffness in Fig. 5(a) is the initial stiffness of the each equivalent DOF before the test and is obtained using the static condensation method [4]. It can be seen that the identified initial stiffness matches well with the calculated stiffness before the test and the largest initial estimation error is 5.7%. In addition, no significant stiffness degradation is identified for the first, fifth and sixth DOF (DOF1, DOF5 and DOF6). These results indicate that these floors were behaving within a totally elastic response without damage when subject to the SHW1 event. However, linear stiffness for the second, third and fourth DOF (DOF2, DOF3 and DOF4) dropped 24%, 23% and 21% compared to the initial stiffness after SHW1, respectively. These changes occur between 3~6 seconds, which corresponds to the stronger motion period of SHW1, providing a further qualitative validation.

SHW2 is much stronger than SHW1, seen in the significant stiffness degradation for the test building identified for all DOFs for SHW2. In particular, the stiffness for the previously

undamaged first, fifth and sixth DOF (DOF1, DOF5 and DOF6) dropped 35%, 37% and 27%, respectively, compared to initial calculated stiffness value. In addition, the stiffness for the previously damaged second, third and fourth DOF (DOF2, DOF3 and DOF4) dropped 50%, 53%, and 54%, respectively, from the calculated initial, pre-testing stiffness, and significantly further from the reduced value seen after SHW1. Visual inspection after SHW2 showed vertical cracks at the beam-column joint connection at floors 4, 5 and 6, which corresponds to the large drop of stiffness reported for the second, third and fourth reduced DOF (DOF2, DOF3 and DOF4).

Structure B

The post-pinching elastic range became negligible during the WL event when the ground motion is small. Thus, only stiffness values for the pinching and/or hybrid range were identified to characterize structural degradation. Fig. 4 shows the identified evolution of the effective pinching stiffness, K_{eff} , for each DOF of Structure B subjected to EI, SHW, WL and SF, sequentially. Again, effective stiffness values were identified consistently between events, so the identified final stiffness of the nonlinear SHW event matched well with the identified initial stiffness of the linear WL event, and also the identified final stiffness of WL event matched well with the initial stiffness of the following nonlinear SF event. The calculated fundamental frequencies using the identified effective stiffness also match well with the experimental frequency from transfer function with the average error less than 3% [5], indicating HLA can track stiffness values automatically across events for both linear and nonlinear response without human input.

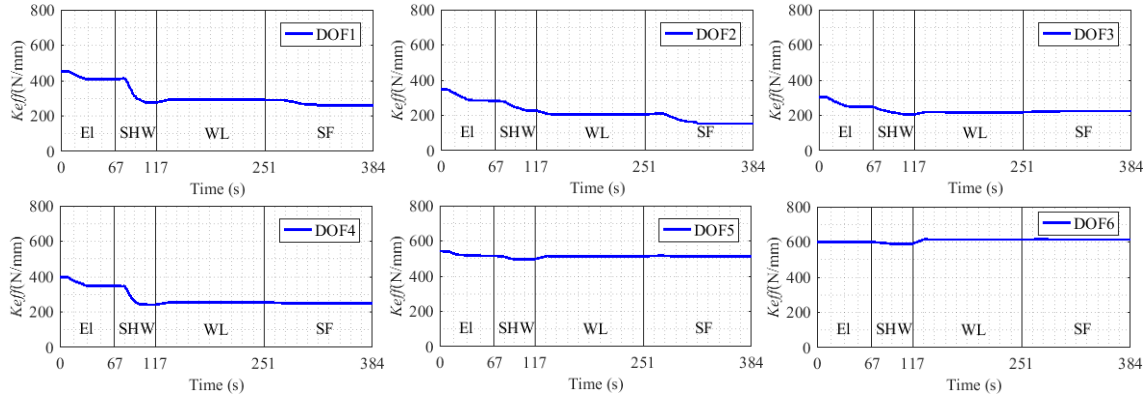


Figure 6. Identified evolution of the effective stiffness K_{eff} for each DOF over 4 events.

Structure C

Finally, Figs 7 and 8 show the evolution of identified elastic stiffness k_e for each story of full scale Structure C for the 6 earthquake events of Table 1 in the x -direction and y -direction, respectively. The solid line, km , represents the results from simple moving average (SMA) of the slope values, and the dashed line, kw , shows the results from the wavelet multiresolution analysis (MRA) analysis [6]. The identified stiffness, k_e , matched well across earthquake events for all stories in both x and y , where the average differences between the final and subsequent initial stiffness over all comparison cases are less than 5%, validating the continuity and accuracy of the identification approach for a real, complex structure across different earthquake events, and thus indicating the ability to use HLA in long term monitoring. Finally, changes of stiffness are tracked over time at each floor, providing significant advantages and insight, particularly in damage level

and localization, over traditional frequency based methods.

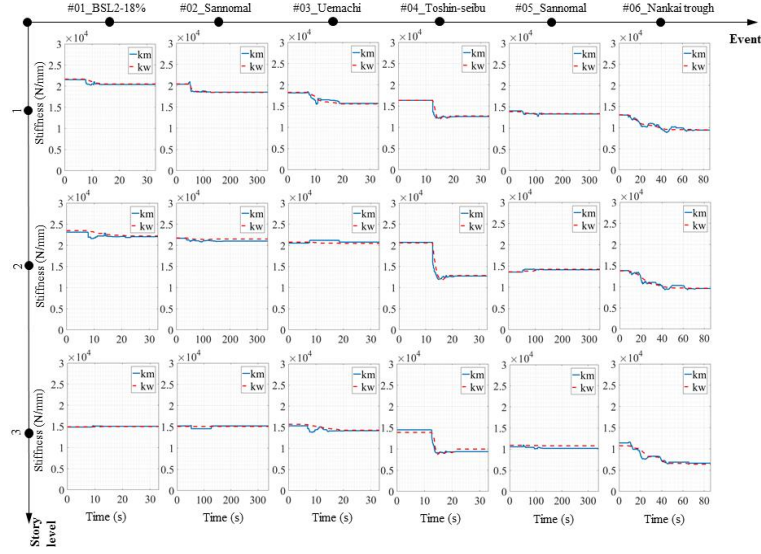


Figure 7. Identified evolution of effective stiffness (k_e) in the x -direction over events.

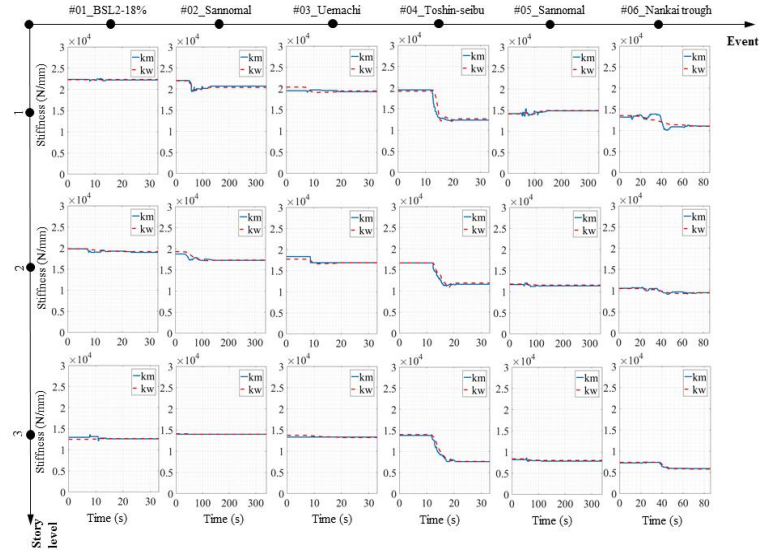


Figure 8. Identified evolution of effective stiffness (k_e) in the y -direction over events.

Conclusions

This research provides unique and wide ranging experimental validation of the model-free, mechanics-relevant stiffness HLA identification method for damage assessment and structural health monitoring. Severity assessment and localization of structural degradation for damaged floors in these MDOF cases is achieved by tracking the changes in structural stiffness over time, if damage occurs in those layers. The identified elastic stiffness matched very well across multiple earthquake events for both MDOF RC and SMRF experimental buildings, validating the continuity and accuracy of the method. The overall results show the HLA method offers significant advantages over parametric model-based methods. It is fully generalizable to different types of

structural behaviours, and requires far simpler computation than genetic algorithms and many other nonparametric algorithms whose convergence and speed are not always guaranteed. The overall results for all structures across all events, including full scale tests, thus validate the approach including all relevant uncertainty, nonlinearity and complexity, providing significant validation well beyond other published SHM methods with only numerical analysis and/or laboratory small scale structure tests.

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